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LATE QUATERNARY RELATIVE SEA-LEVEL CHANGE ON THE WEST COAST OF NEWFOUNDLAND*

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ABSTRACT Two revised relative sea-level (RSL) curves are presented for the Port au Choix to Daniel's Harbour area of the Great Northern Peninsula, northwestern Newfoundland. Both curves are similar, showing continuous emergence of 120-140 m between 14 700 cal BP and present. The half-life of exponential curves fit to the RSL data is 1400 years and the rate of emergence varies from ~2.3 m per century prior to 10 000 cal BP to ~0.13 m per century since 5000 cal BP. The curves fit a general pattern of RSL history along the west coast of Newfoundland, where there is a southward transition from solely emergence to emergence followed by submergence. Isostatic depression curves are generated for four RSL records spanning the west coast. Almost double the crustal depression is recorded to the northwest, reflecting the greater glacioisostatic loading by the Laurentide Ice Sheet over southern Labrador and Québec compared to a smaller loading centre by a regional ice complex over Newfoundland. Only the St. George's Bay RSL record in the southwest appears to show evidence for a proglacial forebulge, when at 6000 cal BP an isostatic ridge of 4 m amplitude begins to collapse.

RÉSUMÉ *Variations du niveau marin relatif de la côte ouest de Terre-Neuve au Quaternaire tardif.* Deux courbes du niveau marin relatif (NMR) sont présentées pour la région allant de Port-au-Choix à Daniel's Harbour sur la Grande Péninsule Nord, au nord-ouest de Terre-Neuve. Les deux courbes sont semblables, montrant une émergence continue de 120 à 140 m entre 14 700 cal BP et l'actuel. La demi-vie des courbes exponentielles ajustées au NMR est de 1400 ans, et le taux d'émergence varie de ~2.3 m par siècle avant 10 000 cal BP à ~0.13 m par siècle depuis 5000 cal BP. Les courbes s'ajustent au modèle général de l'histoire du NMR de la côte ouest de Terre-Neuve, où il existe une transition d'émergence seule à une émergence suivie d'une submergence, en allant vers le sud. Des courbes de dépressions isostatiques préliminaires sont générées pour quatre chronologies du NMR couvrant la côte ouest. Presque le double de la dépression de la croûte est enregistré au nord-ouest, reflétant la charge glacio-isostatique plus grande de l'Inlandsis Laurentidien sur le sud du Labrador et du Québec comparée à la charge plus faible du complexe glaciaire régional localisé sur Terre-Neuve. Seules les données du NMR de St. George's Bay, au sud-ouest, semble démontrer l'affaissement du bourrelet périphérique lorsqu'une vague isostatique de 4 m d'amplitude commence à s'effondrer vers 6000 cal BP.

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INTRODUCTION

Postglacial isostatic rebound is recognized as an important component of local relative sea-level (RSL) change which may either enhance, or subdue the influence of eustasy on sea level trend at a particular location. RSL indicators, used to interpret postglacial sea-level change records, show the composite effects of glacioisostasy, tectonic activity, hydroisostasy, and eustatic sea-level rise, confounding the determination of the full magnitude of isostatic rebound. In addition, the influence of isostatic rebound on local RSL is expected to vary spatially and temporally, depending on the position of the study site with respect to the margin of the former ice load and deglacial history (Andrews, 1987).

In this paper two revised RSL curves are presented for adjacent areas of the Northern Peninsula, northwestern Newfoundland (Fig. 1A-B), based on new and published data. This region is of particular interest from the standpoint of sea-level studies and geodynamical modelling because it is here that the transition from rising to falling sea level, known as the glacioisostatic hinge, apparently intersects the west coast of the island (Liverman, 1994). In addition, the almost perpendicular orientation of the west coast of Newfoundland to the regional isobase pattern (Fig. 1D) and hence the former maximum loading of the Laurentide Ice Sheet, affords the opportunity to assess the influence of glacioisostatic adjustment on postglacial sea-level change across a relatively small area.

The passage of a marginal forebulge from southeast to northwest across Newfoundland is predicted by regional geodynamical models to produce variable sea-level curves around the island; submerging coasts to the south and east, and an emergent coast to the northwest (Quinlan and Beaumont, 1981). Existing RSL data broadly confirm the modelled pattern, although the data mostly consist of emergent features that date to initial establishment of higher sea levels in the late Wisconsinan and early Holocene (~17 000-8500 cal BP), with much less coverage spanning the mid to late Holocene (~8000-2000 cal BP) when sea levels were lower than present (Liverman, 1994; Shaw and Forbes, 1995; Shaw *et al.*, 2002). The west coast of Newfoundland has been the focus of several RSL studies over the last decade or so (Clark and Fitzhugh, 1992; Grant, 1992, 1994; Batterson and Catto, 2001; Daly, 2002; Bell *et al.*, 2003; Bell *et al.*, 2005; Smith *et al.,* 2005) such that there is now a sufficient database with which to critically examine the proposed migration of a marginal forebulge. Because of the apparent role of glacioeustasy in the RSL history of southwest Newfoundland, Bell *et al.* (2003) suggested that a broader re-evaluation of the relative roles of glacioisostatic and glacioeustatic components in the postglacial sea-level record of the island was necessary.

Proximity to the sea has always been, and will likely remain, an important determinant in the location of human settlement in Newfoundland. Consequently, the RSL record has important implications for understanding the magnitude and potential impacts of future sea-level change on coastal communities and resources (Shaw *et al.,* 1998), as well as the interpretation of prehistoric settlement and subsistence patterns (Rast *et al.,* 2005; Renouf and Bell, 2006). For example, Bell and Renouf (2004) argued that the variable and complex postglacial RSL around Newfoundland is linked to the uneven distribution of late Maritime Archaic Indian (MAI) sites (6300-3400 cal BP) and the apparent absence of early MAI sites (8900-6300 cal BP), despite their presence in nearby southern Labrador.

STUDY AREA AND APPROACH

The study area spans a 60-km stretch of coast from Eddies Cove West to south of Bellburns on the west central coast of the Northern Peninsula (Figs. 1A and 2). The physiography of the peninsula is dominated by the Long Range Mountains, composed of Precambrian gneiss, which forms an upland plateau up to 600 m high and 50 km wide, stretching from Hare Bay to Port aux Basques (Fig. 1A). The West Newfoundland coastal lowland comprises a relatively low-relief (≤50 m), narrow swath (2-25 km) of Ordovician sedimentary strata which abuts the Long Range Mountains along a steep escarpment to the south and a gentler ramp to the north (Grant, 1994). The Long Range Mountains supported a local ice cap during the last glaciation, which coalesced with Laurentide ice from southern Labrador and flowed southwestward through the Gulf of St. Lawrence and eastward to the Labrador Sea (Grant, 1994). Deglaciation of the lowland commenced as early as 15 000 cal BP (~13 000 ^{14}C BP), while local uplands were ice-free by 13 500 cal BP (Fig. 1D; Gosse *et al.,* 2006). Upon ice retreat the sea inundated the glacioisostatically depressed coastal lowlands to 140 m above sea level (asl), which resulted in a marine limit shoreline more or less at the foot of the Long Range escarpment. Grant (1994) named this postglacial submergence around the Gulf of St. Lawrence the Goldthwait Sea. Isopleths on the marine limit of the Goldthwait Sea extend eastwards from the Québec North Shore and intersect the west coast of Newfoundland at right angles, declining from 150 m asl in the north (Strait of Belle Isle) to 0 m asl in the south (Port aux Basques), though local variations were controlled by ice retreat patterns (Bell *et al.,* 2003).

Initial postglacial emergence of 4.3 m per century in the study area was thought by Grant (1994) to have been interrupted by a sea-level stillstand at 11 000 ^{14}C BP, possibly induced gravitationally by the local Younger Dryas Ten Mile Lake glacial re-advance. Two models of post-11 000 ^{14}C BP emergence were proposed: in the northern part of the region there was a continuously falling RSL to the present, whereas in the south, the sea fell below its present level at 8000 ^{14}C BP, and slowly rose over the last 5000 years (Grant, 1994). In addition, Grant (1994) speculated that a minor sea-level fluctuation (~10 m) between 2000 and 3000 ^{14}C BP may best explain some paleo sea-level observations for the region. Recent studies, however, employing the 'lake isolation' method have demonstrated that these proposed sea-level changes did not occur, at least in the area between Port au Choix and Brig Bay (Smith *et al.,* 2005).

In this paper we apply a broad range of paleo sea-level data to reconstruct the RSL history of the Port au Choix to Daniel's Harbour region (Fig. 2). Because the postglacial isobase pattern runs more or less perpendicular to the west coast of the Northern Peninsula (see for example the ~15 ka cal BP isobase pattern in Fig. 1D; Grant, 1989; Shaw *et al.,* 2002), the magnitude and timing of RSL changes are

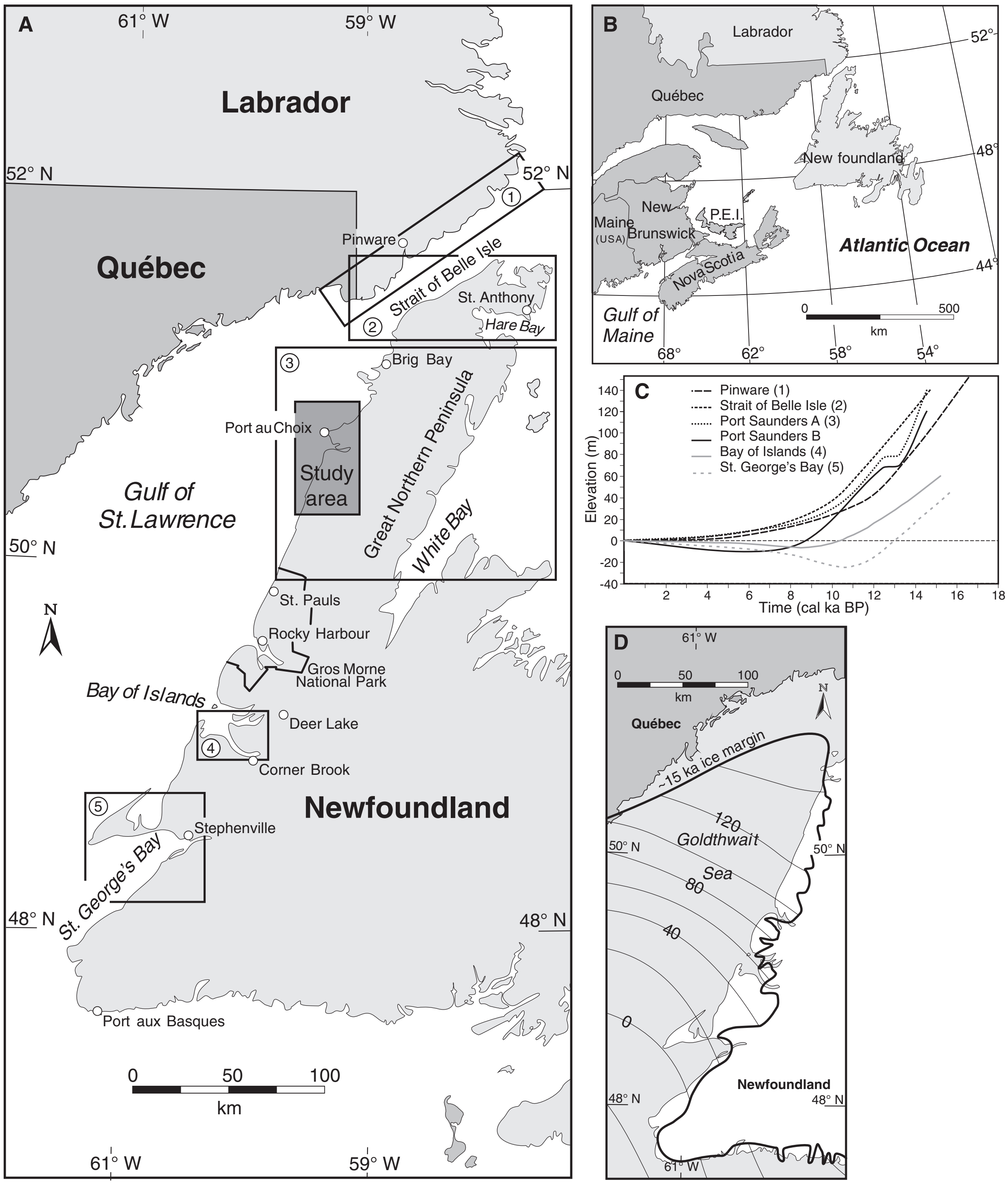

FIGURE 1. (A) Location of study area (shaded box) on the west coast of the Great Northern Peninsula, northwestern Newfoundland, Atlantic Canada (B). Open boxes indicate sampling areas from which radiocarbon-dated paleo sea-level indicators were used to reconstruct the published RSL curves shown in (C). See text for reference citations for individual curves. (D) Mapped and interpolated ice margin along the west coast of Newfoundland at ~15 000 cal BP (compiled from various sources and reproduced in Shaw *et al.,* 2006). Isolines represent isobase elevations on the Goldthwait Sea in metres above sea level, also for ~15 000 cal BP (from Shaw *et al.,* 2002).

(A) Localisation du site à l'étude (zone ombragée) sur la côte ouest de la Grande Péninsule Nord au nord-ouest de Terre-Neuve, Canada Atlantique (B). Les zones ouvertes indiquent les sites d'échantillonnage d'où proviennent les indicateurs d'anciens niveaux marins datés au radiocarbone ayant ailleurs aussi servis à la reconstruction de la courbe de NMR publiée et apparaissant en (C). Consultez le texte pour les citations relatives à chaque courbe. (D) Marge glaciaire cartographiée et interpolée le long de la côte ouest de Terre-Neuve à 15 000 cal BP (compilée à partir de différentes sources et reproduite dans Shaw et al.*, 2006). Les isolignes représentent les niveaux d'élévation de la Mer de Goldthwait en mètres au-dessus du niveau marin, aussi pour ~15 000 cal BP (d'après Shaw* et al.*, 2002).*

likely to vary significantly over short distances along the coast. Hence, two RSL curves for the region were reconstructed: one representing the coastal lowlands between Eddies Cove West and Hawke's Bay, roughly within 20 km of Port au Choix (the Port au Choix curve) and another between River of Ponds and Daniel's Harbour (the Bellburns curve; Fig. 2).

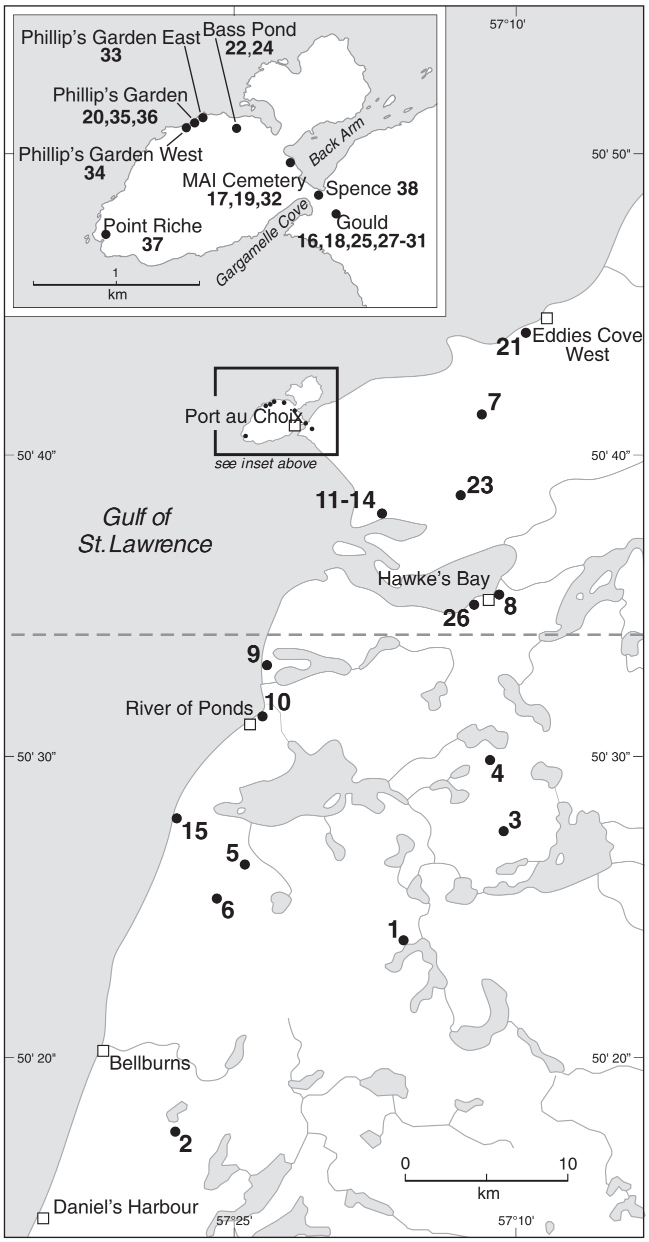

FIGURE 2. Location of study area and radiocarbon-dated sample sites described in Table I and plotted on Figure 3. Samples were selected to reconstruct RSL curves for either Port au Choix or Bellburns depending on their location north or south of dashed line, respectively.

Localisation du site à l'étude et des échantillons datés au radiocarbone décrits au tableau I et montrés sur la figure 3. Les échantillons ont été sélectionnés pour la reconstruction des courbes de NMR pour la localité de Port au Choix ou de Bellburns, selon leur emplacement respectif au nord ou au sud de la ligne tiretée.

PALEO SEA-LEVEL DATA

Various shoreline features and deposits are diagnostic of former sea levels, and when dated using their associated fossils, serve to outline the course of postglacial sea-level change. The upper limit of marine submergence is typically marked by deltas recording where glacier-fed rivers entered the sea. Lower sea-level positions are recorded by various coastal landforms, including beaches, sea cliffs and wave-cut terraces. A total of 38 radiocarbon-dated samples are used in this study to provide temporal control on former sea-level positions (Fig. 3; Table I). The samples consist of marine shell (21), charcoal (7), plant remains (6), organic mud (2), human bone (1) and charred material (1). About 45% of the samples are from a terrestrial/freshwater stratigraphic setting and therefore define an upper limit to the RSL position. The remaining samples are from deep to shallow-water marine environments and provide at least a minimum estimate on their contemporary sea-level elevation.

SAMPLE ELEVATION DETERMINATION

The accuracy of sample elevations depends on the survey instrument when measured and the accuracy rating for topographic map contours when interpolated. Most of the sample elevations in Table I were determined by barometric altimeter, which is accurate to ±2 m, but may be larger depending on atmospheric pressure variability and length of survey traverse from a known datum. In contrast, older sample with elevations interpolated from contours on local 1:50 000 National Topographic Series maps have at best vertical accuracies of ±20 m, because of the low accuracy ratings associated with these maps (NATO class A 1). Such poor elevation control on paleo sea-level samples restricts their usefulness in delimiting the former position of the sea at a dated time interval. For this reason, on Figure 3, vertical error bars are drawn for those samples with elevation accuracies greater than ±5 m.

RADIOCARBON CALIBRATION

Radiocarbon calibration for this study was carried out using the computer program Calib version 4.4html (Stuiver and Reimer, 1993). Normalized radiocarbon ages with 1-sigma standard deviation were input to the program. For non-marine samples, the atmospheric data set INTCAL98 was used (Stuiver *et al.,* 1998a). Organisms from marine environments have been exposed to different levels of ^{14}C than their counterparts in subaerial and aquatic environments and therefore a different calibration data set MARINR98 is used (Stuiver *et al.*,1998b). This marine calibration incorporates a time-dependent global ocean reservoir correction of about 400 years, which must be adjusted to accommodate local effects (ΔR). Dyke *et al.* (2003) have determined that the marine reservoir correction for the Gulf of St. Lawrence is roughly 610 years and so a ΔR value of +210 years was used. For samples derived from a mixture of marine and terrestrial carbon, such as bones of humans who relied heavily on marine food resources or marine mud with a freshwater input, the percent of marine carbon is first determined or estimated and a "mixed" atmospheric and marine calibration data set is used.

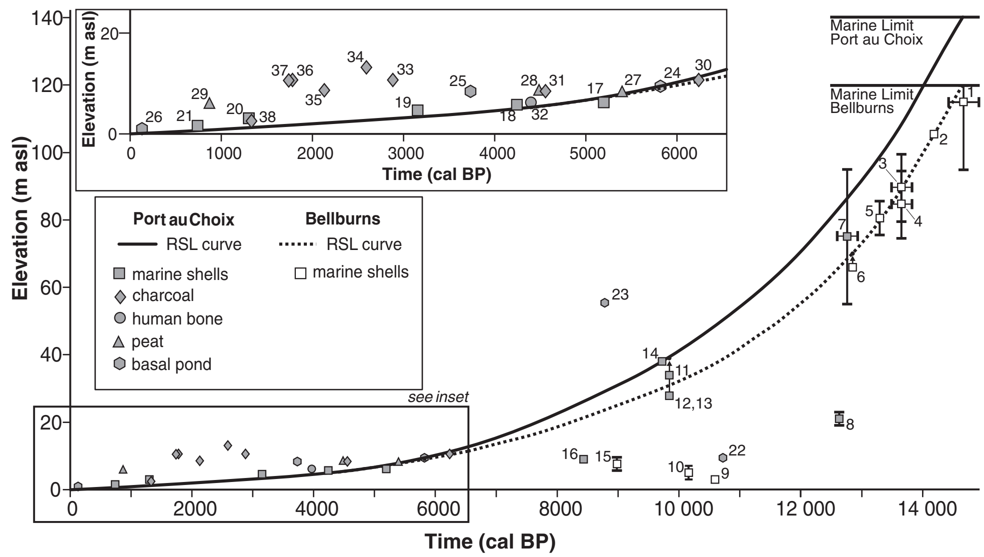

FIGURE 3. Relative sea-level curves fitted to Port au Choix (shaded symbols) and Bellburns data (open symbol). Vertical error bars are shown for those samples with elevation ranges exceeding ±5 m. Details of sample location and description are presented in Table I. With the exception of sample 6, which provides a sea-level index point for the Bellburns curve, the RSL data are used to constrain a best-fit emergence curve for each of the two areas.

Courbes de niveau marin relatif ajustées aux données de Port au Choix (symbole ombragé) et de Bellburns (symbole ouvert). Les barres d'erreur sont présentées pour les échantillons dont la gamme d'élévation est supérieure à ±5 m. Les détails de l'emplacement et de la description des échantillons sont présentés au tableau I. Mise à part l'exception de l'échantillon 6 qui donne un point de référence du niveau marin pour la courbe de Bellburns, les données de NMR sont utilisées pour définir la courbe d'émergence la mieux ajustée pour chacune des deux localités.

In the case of samples GSC-5661 and GrA-6478, where $\delta^{13}C$ values suggest a marine carbon influence but the amount is unknown, a value of 50% is assumed for the age calibration method. The full 2-sigma probability age range is listed for each sample in Table I, whereas the median probability age is plotted on Figure 3.

RADIOCARBON-DATED SAMPLES

The only radiocarbon date related to a known paleo sea-level indicator is from marine shells collected from deltaic sediments on the Bateau Barrens which provided a calibrated age range of 13 130-13 480 cal BP (11 390 ± 60 ^{14}C BP) on a former sea level at 70 m asl, recorded by the delta surface (site 5, Fig. 3; Table I).

Nine raised beaches, ranging in elevation from 115 to 1.5 m asl were radiocarbon dated. The two highest beaches occur well inland of the present coast and are over 14 000 years old (12 000 ^{14}C BP, sites 1-2). Shells were recovered from the upper (6.1 m asl) and lower (4.5 m asl) raised beaches at the MAI cemetery, and from beach sediments underlying the MAI Gould site, both locations are in Port au Choix town site (sites 16-19). Another shell sample was collected from the lowest terrace (4.5 m asl) at the Dorset Paleoeskimo Phillip's Garden site on the Point Riche Peninsula (site 20). Grant (1994) dated shell samples from the first raised beach above high tide level at Eddies Cove West (site 21) and from below a marine terrace at 7.6 m asl near Lafontaine Point (site 15).

Shell samples from sublittoral sediments that have little or no stratigraphic context provide ages for a sea-level position at some unknown height above the collection site (sites 3-5, 7-10). For example, fossiliferous marine clays exposed near present sea level at River of Ponds were likely deposited in many 10s of metres water depth about 10 000 years ago (sites 9-10).

Ecological information on the species dated may help to refine paleo water depth. The spirally arranged, calcareous white tubes of *Spirorbis borealis* (polychaete worm) were found on wave-rounded bedrock at 21 m asl near Hawke's Bay (site 8). These worms are commonly observed today on the fronds of seaweed and on rocks and mollusc shells in as much as 30 m water depth (J. Maunder, Newfoundland Museum, pers. comm., 2004). A sample of tubes provided a calibrated age range of 12 310-12 960 cal BP (10 710 ± 90 ^{14}C BP; site 8, Table I).

A gravel pit in the town of Port Saunders exposes horizontally, interbedded sand and gravelly sand capped by boulder gravel in a 5-10 m high section below a marine terrace at 40 m asl. The sedimentary sequence is tentatively interpreted to represent sublittoral deposition on a barrier beach or spit, overlain by debris flow deposits, primarily large boulders (Grant, 1994). Radiocarbon-dated mussels of *Mytilus edulis* in the sand and barnacles (*Balanus crenatus*) on the boulders provided overlapping ages of about 9800 cal BP (8750 ^{14}C BP; sites 11-14, Table I).

Smith *et al.* (2005) used diatoms to identify when Otter Pond (site 26) was most likely isolated from the sea. The pond record indicates that RSL was within 0.5 m of its present elevation in the last 150 years or so. In sampled ponds where sediment was devoid of diatoms (Field Pond) or diatom analysis was not carried out (Bass and Stove ponds), the lowermost dated level in the freshwater component of the sediment

TABLE I

Radiocarbon dates and descriptions of samples used to reconstruct relative sea-level history in the Port au Choix region

Site[a]	^{14}C age[b] (BP)	Laboratory number	Calibrated ^{14}C age[c] (BP)	Sample elevation[d]	Relative sea level elevation (m)	Material dated[e]	Geological context	Location	Reference[f]
1	12 390 ± 160	GSC-1600#	14 530 (14 670) 15 370	115 ± 20†	>115 ± 20	Me	Beach gravel	Flat Pond	2
2	12 190 ± 360	GSC-1485#	13 540 (14 170) 14 420	106 ± 2	>106 ± 2	Ha	Sandy veneer	Zinc Pond	2
3	11 790 ± 170	GSC-1601#	13 400 (13 630) 14 050	90 ± 10‡	>90 ± 10	Mt	Gravelly marine veneer	Eastern Blue Pond	2
4	11 790 ± 160	GSC-1605#	13 400 (13 630) 14 050	85 ± 10‡	>85 ± 10	Mt	Sandy gravel	River of Ponds	2
5	11 390 ± 90	GSC-4538	13 130 (13 280) 13 480	81 ± 5‡	>81 ± 5	Mt	Sand	Bateau Barrens	6
6	10 870 ± 60	Beta-149995#	12 630 (12 850) 13 010	67 ± 2	70	Mt	Gravel foresets	Bateau Barrens	10
7	10 790 ± 180	GSC-2919#	12 570 (12 760) 13 010	75 ± 20†	75 ± 20	Mt	Stratified silt below gravel	Bustard Cove	3
8	10 710 ± 90	TO-9168	12 310 (12 630) 12 960	21 ± 2	>21 ± 2	Sb	Attached to bedrock	Hawke's Bay	8
9	9410 ± 170	GSC-4629	10 290 (10 590) 10 830	2.6\$	>2.6	Marine shells, see taxa in ref. 6	Silty clay	Little Brook Pond	7
22	9380 ± 150	GSC-5661	10 380 (10 720) 10 870	9*	9	Marine organic sandy mud	Marl (200-210 cm)	Bass Pond	9
10	9090 ± 100	GSC-4644	9840 (10 160) 10 320	5	>5	Hp, Vb, Ci	Stony clay	River of Ponds	7
11	8790 ± 80	GSC-3998	9560 (9860) 10 150	34 ± 2‡	34-40	Me	Gravel	Port Saunders	8
12	8780 ± 80	TO-9164	9500 (9840) 10 160	28 ± 2‡	28-40	Me	Gravelly sand	Port Saunders	8
13	8760 ± 80	TO-9165	9480 (9800) 10 150	28 ± 2‡	28-40	Me	Gravelly sand	Port Saunders	8
14	8710 ± 80	TO-10947	9430 (9720) 10 040	38 ± 2‡	38-40	Bc	Boulder gravel	Port Saunders	8
15	8090 ± 200	GSC-1768#	8760 (8980) 9130	7.6 ± 2	>7.6 ± 2	Mp	Sand	Lafontaine Point	2
23	7920 ± 130	Beta-32598	8420 (8780) 9030	55*	55	Organic mud	Organic mud (180-187 cm)	Stove Pond	9
16	7570 ± 90	Beta-107796	8200 (8430) 8630	9 ± 1	>9 ± 1	Nl	Beach gravel	Gould site, Port au Choix	8
30	5440 ± 50	Beta-148518	6170 (6230) 6310	10.5 ± 0.01	<10.5 ± 0.1	Charcoal	F502 in unit 3, area 99-2 (E)	Gould site, Port au Choix	10
24	5100 ± 50	Beta-115782	5730 (5820) 5930	9*	9	Conifer Bark	Marl (92 cm)	Bass Pond	9
27	4670 ± 120	TO-8518	5030 (5390) 5610	7.89 ± 0.01	<7.89 ± 0.01	Ericaceae stem fragments	Peat (122.5 cm)	Gould site, Port au Choix	10
17	4480 ± 130	GSC-1403#	4970 (5190) 5340	6.1 ± 0.3	>6.1 ± 0.3	Mp	Sand	MAI cemetery, Port au Choix	1
32	4220 ± 50	GrA-6478	4249 (4391) 4591	6.1§	<6.1	Human bone	Burial A1B from Locus II	MAI cemetery, Port au Choix	8
31	4060 ± 50	Beta-146081	4420 (4550) 4650	8.32 ± 0.01	<8.32 ± 0.01	Charcoal	F515 in level 3x	Gould site, Port au Choix	10
28	4010 ± 160	TO-8520	4070 (4480) 4860	8.23 ± 0.01	<8.23 ± 0.01	Charcoal, Ericaceae leaf, bark	Peat (79 cm)	Gould site, Port au Choix	10
18	3770 ± 80	Beta-149994#	4000 (4240) 4430	5.62 ± 0.2	>5.62 ± 0.2	Nl	Beach gravel	Gould site, Port au Choix	8
25	3460 ± 40	Beta-151259	3630 (3730) 3830	7.9*	7.9	Plant material	Marl (54.5 cm)	Field Pond, Gould site	10
19	2900 ± 130	GSC-1318	2970 (3150) 3320	4.5 ± 0.3	>4.5 ± 0.3	Ma	Sand	MAI cemetery, Port au Choix	1
33	2760 ± 90	Beta-23979#	2740 (2880) 3080	10.5§	<10.5	Charcoal	Level 3 NW of House Feature 2	Phillip's Garden East	10

TABLE I (continue)

Radiocarbon dates and descriptions of samples used to reconstruct relative sea-level history in the Port au Choix region

Site[a]	^{14}C age[b] (BP)	Laboratory number	Calibrated ^{14}C age[c] (BP)	Sample elevation[d]	Relative sea level elevation (m)	Material dated[e]	Geological context	Location	Reference[f]
34	2540 ± 160	Beta-49759#	2300 (2590) 2970	13§	<13	Charcoal	F21 in midden F5 (level 2)	Phillip's Garden East	10
35	2140 ± 100	Beta-23976#	1920 (2130) 2340	8.5§	<8.5	Charcoal	F19 in House Feature 14	Phillip's Garden	10
36	1850 ± 110	Beta-15379#	1530 (1780) 2010	10.5§	<10.5	Charcoal	F6 in House Feature 1	Phillip's Garden	10
37	1810 ± 40	Beta-160978	1690 (1740) 1830	10.41§	<10.41	Charred material	F49	Point Riche	10
38	1420 ± 70	Beta-49754	1230 (1330) 1420	2.4§	<2.4	Charcoal	Hearth F9	Spence site, Port au Choix	10
20	1350 ± 80	Beta-107797#	1150 (1300) 1480	3 ± 1	>3 ± 1	Nl	Beach gravel	Phillip's Garden	8
29	970 ± 120	TO-8522	740 (870) 970	5.59 ± 0.01	<5.59 ± 0.01	Ericaceae stems	Peat (129.5 cm)	Gould site, Port au Choix	10
21	380 ± 130	GSC-1602#	640 (740) 880	1.5 ± 0.5	>1.5 ± 0.5	Me	Pebble gravel	Eddies Cove West	2
26	130 ± 40	Beta-151259	10 (130) 150	1.5*	0.5	*Picea* needles	Gyttja (5.5 cm)	Otter Pond, Hawke's Bay	8

a. See Figure 2 for location of sample sites.

b. All dates, except those on marine shell samples with GSC laboratory designations or marked with a # symbol, have been corrected (normalized) for fractionation to a base of δ^{13}C = -25‰, and where applicable have been adjusted for a marine reservoir effect of 610 years. GSC shell dates have been normalized to a base of δ^{13}C = 0‰, which is roughly equivalent to a fractionation correction to a base of δ^{13}C = -25‰ and a marine reservoir correction of 400 years. An additional 210-year correction has been applied to these dates to make them equivalent to other dates on marine carbonates. Dates with a # symbol have estimated δ^{13}C values, based on values typical of the material type. Unconventionally, GSC date errors represent two standard deviation. Samples GSC-5661 and GrA-6478 have an undetermined amount of marine carbon and therefore no marine reservoir correction has been applied to them.

c. Calibration procedure and data sets are described in the text.

d. Sample elevation for sediment core dates (*) is given as pond elevation. Elevation for archeological samples (§) is given as elevation of associated terrace, except for samples from the Gould site, where surveyed elevations are available. Elevations measured with an altimeter (‡) have an error of at least ±2 m; larger errors cited in Grant (1992). Elevations interpolated from local topographic maps (†) which have a NATO accuracy rating of A-3, have vertical errors of ±20 m (A. Wood, personal communication, 2002). Elevation errors revised from those in Grant (1992) are based on information obtained from original field scientists. All elevations are measured relative to high tide, except in one case ($) where mean water level is used.

e. Bc: *Balanus crenatus*, Ci: *Chlamys islandicus*, Ha: *Hiatella arctica*, Hp: *Hemithyris psittacea*, Ma: *Mya arenaria*, Me: *Mytilus edulis*, Mp: *Mya pseudoarenaria*, Mt: *Mya truncata*, Ni: *Nucella lapillus*, Sb: *Spirorbis borealis*, Vb: *Venericardia borealis*.

f. 1: Lowden and Blake (1972), 2: Lowden *et al.* (1977), 3: Blake (1983), 4: Blake (1986), 5: Blake (1987), 6: McNeely and McCuaig (1991), 7: McNeely and Jorgensen (1992), 8: Bell *et al.* (2005a), 9: Bell *et al.* (2005b), 10: this study.

core is used as a minimum estimate on the date of isolation of the freshwater basin. For Field pond (~8 m asl), which is adjacent to the MAI Gould site, a plant macrofossil at 54.5 cm depth in a 78.5 cm-long sediment core provided an age range of 3630-3830 cal BP (3460 ± 40 ^{14}C BP; site 25, Table I). Pollen and sedimentological records suggest that the entire core consists of freshwater sediment (Bell *et al.,* 2005b). For Stove Pond, located at ~55 m asl and 11 km inland of Port au Choix, a bulk sediment sample from between 180 and 187 cm in the 253 cm-long core was radiocarbon-dated at 8420-9030 cal BP (7920 ± 130 ^{14}C BP; site 23, Table I). Although this basal date is close to the transition between organic mud and sandy clay containing marine foraminifera at ~190 cm, the radiocarbon date is considered unreliable (Bell *et al.,* 2005b). Bass Pond is a shallow coastal marl pond at 9 m asl, near the Paleoeskimo sites at Phillips Garden on Point Riche Peninsula. The upper limit of marine sediment at ~145 cm depth in the 210 cm-long sediment core is marked by abundant foraminifera below this level and the rapid increase in *Pediastrum* above this level. A calibrated age of 5730-5930 cal BP (5100 ± 50 ^{14}C BP; site 24, Table I) on conifer bark from 82 cm depth is considered more reliable than one of 10 380-10 870 cal BP (9380 ± 150 ^{14}C BP; site 22, Table I) on bulk marine organic sediment from the 200-210 cm interval (Bell *et al.,* 2005b).

Additional upper constraints on the RSL curve are provided by dates on basal freshwater peat samples from the Gould site (sites 27-29) and the oldest date from each major archeological site in the region (sites 30-38).

RELATIVE SEA-LEVEL HISTORY

The Port au Choix RSL curve records continued emergence since deglaciation. It is anchored at one end by modern sea level and at the other by the height and age of marine limit, which is estimated by Grant (1994) to be ~140 m (from the elevation of local washing limits) and 14 700 cal BP (based on the oldest marine shell sample in the area; site 1, Table I), respectively. The form of the curve is dictated by: (i) the age of four overlapping radiocarbon-dated shell samples (~9800 cal BP; sites 11-14, Fig. 3) projected to the elevation of their probable sea level at 40 m asl; and (ii) interpolation between narrowly-bracketed data points represented on the one hand by a maximum sea-level position recorded by the elevation of freshwater peat (site 27) and on the other, by a minimum sea-level position related to the elevation of marine shells in a raised beach (site 17, Fig. 3). The rate of RSL fall decreases from 2.1 m per century before 10 000 cal BP to 0.13 m per century in the last 5000 years.

The Bellburns RSL curve also depicts a continuously emerging coast from deglaciation until present. The curve is reasonably well constrained prior to 12 000 cal BP, anchored by Grant's (1994) estimate of marine limit elevation and age of ~120 m and 14 700 cal BP (site 1), respectively, and the age of the Bateau Barrens delta (70 m asl) at 12 850 cal BP (site 6, Fig. 3). On average, the rate of emergence for this early postglacial period is 2.3 m per century. Forward projection of the RSL curve post-12 000 cal BP assumes an emergence history similar to that of Port au Choix, which results in a convergence of RSL up to 5000 cal BP, after which the two curves share more or less identical emergence history.

COMPARISON TO PUBLISHED CURVES

The Port au Choix and Bellburns RSL curves are similar in form to the one reconstructed by Grant (1994) for the northern part of his study area (Port Saunders A in Fig. 1C), except there are no data to support his proposed sea-level stillstand between 13 300 and 12 600 cal BP. The single data point (GSC-2919, his site 18; Grant, 1994) that was used to support his interpretation has a vertical error range of ±20 m (our site 7, Fig. 3), too large to resolve the proposed sea-level adjustment.

The Bellburns RSL curve differs from Grant's (1994) Port Saunders B curve (Fig. 1C) in that there is no period of RSL history projected below present and no late Holocene sea-level fluctuation. Although the apparent absence of raised marine deposits postdating 9000 cal BP between Hawke's Bay and Daniel's Harbour (Fig. 2), may be interpreted to reflect a period of RSL lower than present (Liverman, 1994), it may also simply reflect a lack of exposure and research effort. For instance, contrast the amount of RSL data for Port au Choix (Fig. 3), where there has been much coastal development and intense archaeological activity for more than 20 years (Renouf, 1999). Also, the presence of a relict sea cliff 5-10 m high and lying just above high tide along much of the coast between Port au Choix and Daniel's Harbour precluded the formation and preservation of raised marine deposits in this elevation range (Fig. 4A). Finally, diatom records from Otter Pond, Hawke's Bay, are dominated by marine taxa, with a transition to brackish near the top, which indicates that this coastal lake basin only recently became isolated from the sea (Smith *et al.,* 2005). Together, these data support a relatively straightforward RSL record of continuous emergence for the Bellburns study area.

REGIONAL PATTERNS

POSTGLACIAL EMERGENCE

The Port au Choix and Bellburns curves fit a general pattern of RSL history along the west coast of Newfoundland, where there is a southward transition from solely emergence to emergence followed by submergence (a "J-shaped" curve or a "type-B" curve of Quinlan and Beaumont, 1981). RSL curves from Pinware, southern Labrador (Clark and Fitzhugh, 1992), Strait of Belle Isle (Grant, 1992), Port au Choix and Bellburns (this study) are examples of the former, whereas those from Bay of Islands (Batterson and Catto, 2001) and St. George's Bay (Bell *et al.,* 2003) are examples of the latter (Fig. 1C). The transition zone between the two RSL histories must therefore lie along the coast somewhere between Bay of Islands and Daniel's Harbour. A study by Daly (2002) on salt marsh stratigraphy and foraminifera in St. Paul's Inlet, Gros Morne National Park (Fig. 1A), concluded that RSL was falling until ~1000 cal BP, then rose slowly (<0.01 m per century) to the present (Bell *et al.,* 2001). This implies that the transition zone is close to the northern limit of the park and that relatively small overall changes in RSL (~0.1 m) have occurred over the last several millennia in this region. Extensive modern inter-tidal rock platforms in Gros Morne National Park and farther north likely formed during this relatively stable period of RSL history (Fig. 4B).

The half-life of an RSL curve is a common approach to describing the response time of RSL records on a regional scale (Dyke and Peltier, 2000). It assumes that emergence data can be described by an exponential function ($y = ae^{bx}$, where y is elevation (m), x is age (yr), and b is the proportionality constant) and there have been no transgressions during overall emergence. The half-life is the time taken to accomplish half of the remaining emergence and is calculated from the division of the natural logarithm of 2 (0.693) by the proportionality constant (Dyke and Peltier, 2000). For both Port au Choix and Bellburns RSL data the half-life of best-fit exponential curves is 1400 years (r^2 = 0.94 and 0.99, respectively). This corresponds well with the contoured map of half-lives presented for Canada by Dyke and Peltier (2000) and is consistent with values of 1400 and 1100 years calculated by them for Strait of Belle Isle and Pinware curves, respectively. However, it is less than the average of 1700 years calculated for many sites in southern Labrador and southeastern Québec (Dyke and Peltier, 2000).

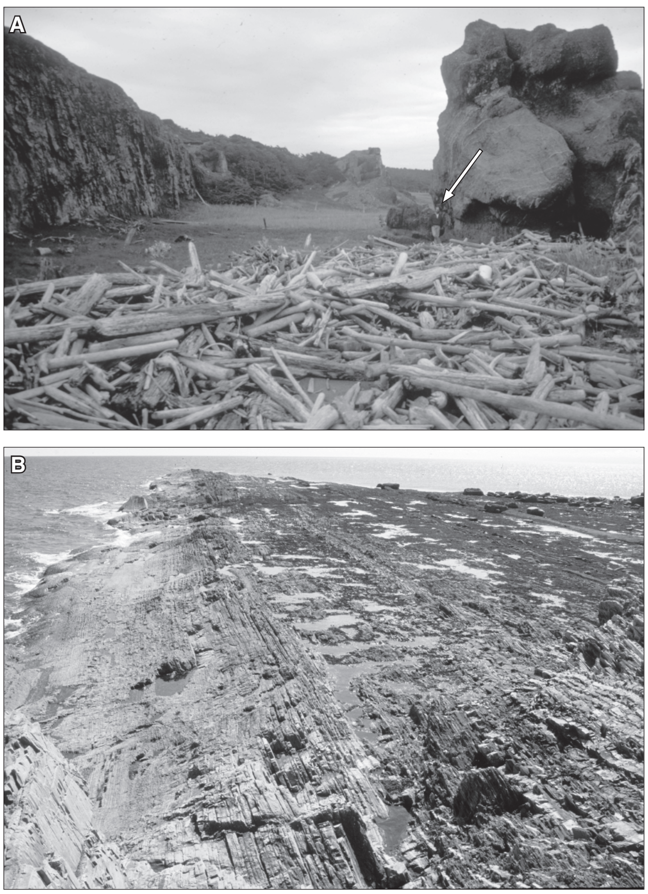

FIGURE 4. (A) Photograph of raised sea cliff and sea stack behind modern storm beach (covered with driftwood) near Bellburns on the west coast of the Great Northern Peninsula. White arrow points to a person leaning against the sea stack. The raised sea cliff extends for 10s of kilometres between Gros Morne National Park and Port au Choix. (B) Shore platform cut in steeply dipping bedrock exposed at low tide near Green Point, Gros Morne National Park. The platform is more than 100 m wide. These extensive intertidal platforms have been attributed in part to a relatively stable sea level over the last several millennia.

(A) Photographie d'une falaise marine surélevée et d'un pilier rocheux d'origine marine situés à l'arrière de la plage de tempête active (couverte de bois) près de Bellburns, sur la côte ouest de la Grande Péninsule Nord. La flèche blanche pointe sur une personne appuyée sur le pilier rocheux. (B) La falaise marine surélevée s'étend sur des dizaines de kilomètres entre le Parc National du Gros Morne et Port au Choix. La plateforme est large de plus de 100 m. Ces vastes plateformes intertidales sont en partie associées à un niveau marin relativement stable depuis les quelques derniers milliers d'années.

CRUSTAL RESPONSE

The pattern of solely isostatic depression can be estimated from the emergence curves assuming that postglacial RSL is primarily a balance of two components: changes in the water volume of the oceans due to the addition of glacier meltwater (eustatic sea-level change) and changes in the level of the Earth's surface due to loading and unloading of glacial ice (glacioisostatic response). This simple approach ignores potential gravitational effects associated with nearby ablating ice masses and hydro-isostatic effects from meltwater loading of the adjacent continental shelf. The eustatic sea-level record can be approximated from 'far-field' sites beyond the influence of glacioisostatic effects. In this study we use the sea-level record for Barbados (Fig. 5A; Fairbanks, 1989) and subtract it from local RSL curves along the west coast of Newfoundland to generate records of isostatic depression (Fig. 5B).

Our description and interpretation of the isostatic depression patterns along the west coast of Newfoundland is intentionally cautious for the following reasons: (1) the Barbados curve is only an approximation of the regional eustatic sea-level history; (2) the RSL curves contain various assumed and interpolated components (see above) that may only be approximations of the true RSL history; (3) in all 4 RSL records the age of marine limit is estimated, not dated directly, which introduces a larger potential error in calculating isostatic depression at a time when crustal rebound is relatively rapid; and (4) during the last several millennia when RSL change appears relatively small (±15 m) and based on rare or imprecise (±2 m) paleo sea-level data, there is a greater potential error in calculating crustal rebound/subsidence rates. We choose 4 RSL curves to represent the full range of postglacial emergence along the west coast of Newfoundland: Port au Choix and Bellburns curves (this study) representing continuous emergence records from the Northern Peninsula; and Bay of Islands and St. George's Bay curves (Batterson and Catto, 2001; Bell *et al.,* 2003) representing "J-shaped" curves from the southwest. In the case of the Bay of Islands curve, we calibrated the radiocarbon dates presented by Batterson and Catto (2001) using the approach outlined above and interpolated a best-fit curve according to their published RSL interpretation (Fig. 5A). For consistency, we re-calibrated the radiocarbon dates from St. George's Bay using Calib 4.4 and adopted the best-fit version of the two RSL curves presented by Bell *et al.* (2003, their Fig. 5), although both versions produced almost identical isostatic depression curves in our exploratory analysis.

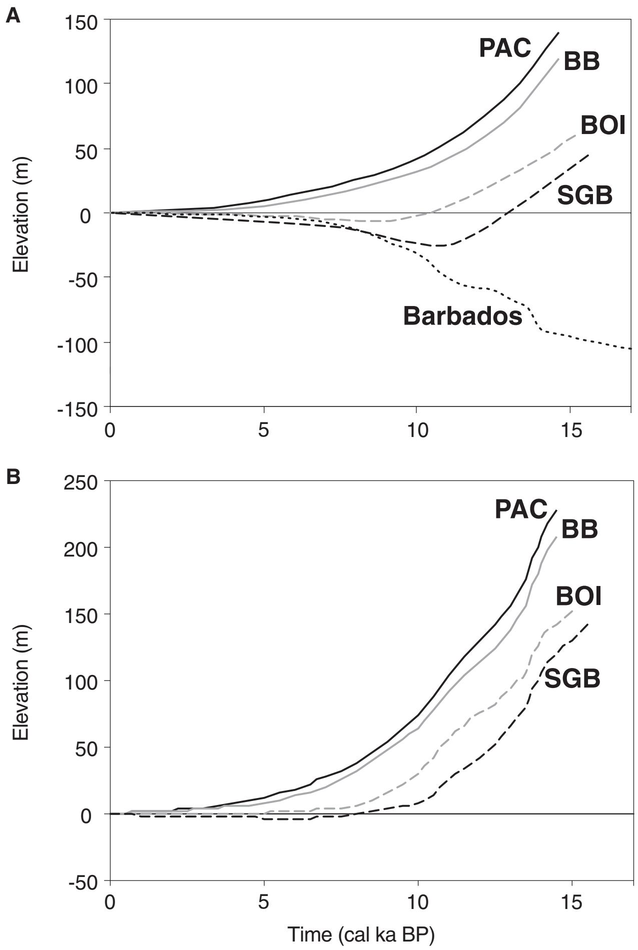

FIGURE 5. (A) RSL curves for Port au Choix (PAC), Bellburns (BB), Bay of Islands (BOI), and St. George's Bay (SGB) and the Barbados far-field "eustatic" sea level curve. See text for data sources and description. (B) Isostatic depression curves for PAC, BB, BOI, and SGB were generated by subtracting the Barbados "eustatic" sea level curve from individual RSL curves in (A).

(A) Courbes de NMR pour Port au Choix (PAC), Bellburns (BB), Bay of Islands (BOI) et St. George's Bay (SGB) et la courbe « eustatique » étalon de la Barbade. Consultez le texte pour la source des données et les descriptions. (B) Les courbes de dépression isostatique pour PAC, BB, BOI, et SGB ont été générées en soustrayant la courbe « eustatique » étalon de la Barbade aux courbes individuelles de NMR présentées en (A).

For comparison, half-lives calculated for the emergence phases only of Bay of Islands and St. George's Bay RSL data gave values of 1200 and 900 years, respectively, (r^2 = 0.97 and 0.91, respectively), which is generally consistent with the regional pattern portrayed by Dyke and Peltier (2000), where a zone of faster rebound (shorter half-lives) occurs towards the former ice margin.

Comparison of the isostatic depression curves indicates almost twice as much crustal depression in the north (230 m; Port au Choix) compared to the south (120 m; St. George's Bay) at 14 500 cal BP, when the entire coast had become ice-free. This trend reflects the greater glacioisostatic loading by the Laurentide Ice Sheet over southern Labrador and Québec compared to a smaller loading centre by a regional ice complex over Newfoundland (Grant, 1989).

FOREBULGE MIGRATION

RSL history at the ice margin is further complicated by the inward migration of the proglacial forebulge that occurs subsequent to deglaciation (Lambeck, 1991). The passage of a forebulge in the record of isostatic depression should be evident in a gradual shift from uplift (diminishing depression) to subsidence (increasing depression). Such a shift is only observed in the St. George's Bay data when at 6000 cal BP an isostatic ridge (negative depression) of 4 m begins to subside (Fig. 5B). The data for Bay of Islands suggest continuous crustal uplift, with little change (<0.5 m) over the last 5000 years; however, given the general absence of geological control on this part of the RSL record, there is a broad error margin within which the passage of a forebulge of several metres amplitude may be concealed. Farther north at St. Paul's Inlet, Daly (2002) interpreted a shift from falling to rising RSL at ~1000 cal BP as potential evidence for the passage of a relatively subdued forebulge on the order of decimetres or less. In contrast, the isostatic depression curves for Bellburns and Port au Choix show no evidence for the passage of a proglacial forebulge. This pattern is consistent with modelling by Quinlan and Beaumont (1981) of the passage of a forebulge from southeast to northwest across Newfoundland towards the former ice sheet centre. Their model output predicts variable RSL curves along the west coast, characterized by recent submergence to the south and emergence to the north.

Assuming a steady forebulge migration over a distance of 150 km from St. George's Bay to St. Paul's Inlet between 6000 and 1000 cal BP, then this produces a migration rate of 30 km per ka. This rate compares favourably with other estimates for the west coast of Newfoundland based on salt-marsh and tide-gauge data (50 km per ka; Daly, 2002) and the raised marine shell record (45 km per ka; Liverman, 1994), although the latter was predicated on forebulge migration between 13 000 and 7000 ^{14}C BP (Liverman, 1994). This rate is also consistent with the rate of forebulge migration calculated between Moosehead Lake (Maine) and Québec City (Balco *et al.,* 1998), but is somewhat lower than the 70-110 km per ka rate estimated for the Gulf of Maine (Barnhardt *et al.,* 1995).

CONCLUSIONS

1- Two revised RSL curves for the Port au Choix region have similar forms, showing continuous emergence of 140 m and 120 m, respectively, between 14 700 cal BP and present. The half-life for exponential curves fit to the RSL data is 1400 years and the rate of emergence varies from ~2.3 m per century prior to 10 000 cal BP to ~0.13 m per century in the last 5000 cal BP.

2- The revised curves differ from curves previously published by Grant (1994) for a larger area of the Great Northern Peninsula in that there is no period of relative sea-level history below present and no late Holocene sea-level fluctuation. The curves do, however, fit the general pattern of

RSL history along the west coast of Newfoundland, where there is a southward transition from solely emergence to emergence followed by submergence.

3- Isostatic depression curves spanning the west coast of Newfoundland show increased crustal depression towards the northwest, reflecting the greater glacioisostatic loading by the Laurentide Ice Sheet over southern Labrador and Québec compared to a smaller loading centre by a regional ice complex over Newfoundland. Crustal tilt declines throughout the postglacial period.

4- Proglacial forebulge collapse and migration may not be as influential on the RSL history of western Newfoundland as geodynamical models suggest. Forebulge migration along the southwest coast is estimated to have been 30 km per ka between 6000 and 1000 cal BP, during which time forebulge amplitude may have declined from 4 m to 0.1 m. More detailed field studies on Late Holocene RSL history are needed to test these estimates.

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